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REGENERATIVE BURNER SYSTEM FOR THERMOELECTRIC POWER SOURCES.(U)
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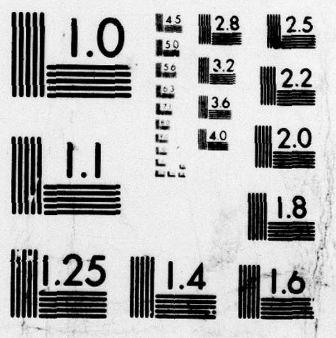

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REGENERATIVE BURNER SYSTEM FOR THERMOELECTRIC POWER SOURCES

G. Guazzoni
J. Angello
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ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

July 1979

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US ARMY ELECTRONICS RESEARCH & DEVELOPMENT COMMAND
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A thermoelectric power source is being developed to provide a multifuel, silent, maintenance free tactical power generator for forward area and unattended-operation applications.

An experimental study of a regenerative burner system for the 500-Watt Thermoelectric Power Source has resulted in significant reduction in fuel consumption and infrared signature of the power source.

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REGENERATIVE BURNER SYSTEM FOR THERMOELECTRIC POWER SOURCES

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Introduction

A thermoelectric power source is being developed to provide a multifuel, silent, maintenance free tactical power generator for forward area applications.

Formal testing of prototype models of the 500-Watt Thermoelectric Power Source has demonstrated its ability as an improved source of power for military equipment in a wide range of environmental conditions. This unit will replace the troublesome gasoline engine-driven generator sets which are noisy, unreliable, and require frequent maintenance.

Maximum efficiency during operation of the thermoelectric power source will assure an effective utilization of fossil fuel in support of Army mission requirements and energy conservation.

This paper describes an experimental study of a regenerative burner system for the 500-Watt Thermoelectric Power Source. Test results not only show significant reduction in fuel consumption, but also indicate that preheating of the primary air for combustion provides a practical solution for the elimination of carbon accumulation in the burner system.

Description of 500-Watt Thermoelectric Power Source

The configuration of the 500-Watt Thermoelectric Power Source is shown in Figure 1.

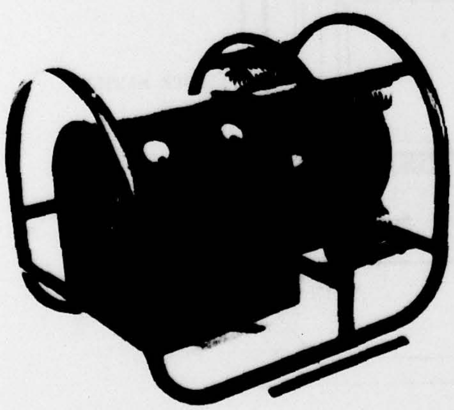

Figure 1. 500-Watt Thermoelectric Power Source (Present Configuration)

The cylindrically shaped thermoelectric converter is horizontally mounted on the right side of the unit. The section on the left encases the cooling fan, the fuel pump, the burner tube, which constitutes the initial part of the burner system, and instrument and control panel. The unit's electronic components are contained in a moistureproof drawer, at the bottom of the unit, easily accessible for maintenance. The outside dimensions of this unit are 63 cm wide, 48 cm long, and 53 cm high.

An integral part of the thermoelectric converter (Figure 2) is the combustion chamber which forms the inside of the cylindrical structure.

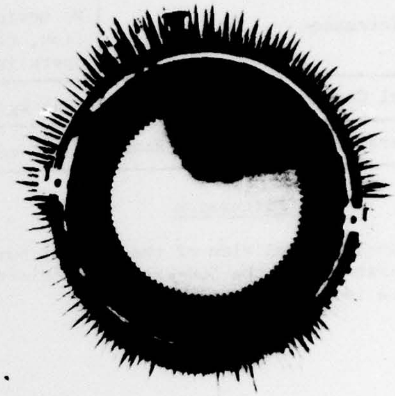

Figure 2. Thermoelectric Converter

The outside shell of the converter features a spine-type cooling fin array. The annular region between the combustion chamber and the cold shell contains the thermopile. End bells are welded to both ends of the converter and provide a hermetically-sealed container for the thermopile. The container is backfilled with argon gas which protects the thermoelectric material from oxidation at high temperature. Two hundred fifty six (256) lead-telluride (PbTe) couples are electrically connected in series to produce a nominal 28 Vdc output.[1] They are arranged in 32 rows, parallel to the cylindrical axis of the combustion chamber, with 8 couples per row. At the operational hot junction and cold junction temperature of 565°C and 162°C, respectively, each couple develops a load voltage of 0.11 Vdc. Raw power from the thermoelectric converter is conditioned by the electronic subsystem by means of a shunt regulator. The electronic subsystem also protects the power source from overload and abnormal load conditions and automatically operates and controls the burner, fuel pump, and cooling fan to ensure that the thermoelectric converter operates at optimum efficiency.

The principal features of the 500-Watt Thermoelectric Power Source are specifically designed to meet Army field requirements of electric power consuming equipments typical of forward area applications. They are shown in Table 1 together with the corresponding characteristics of the 0.5 kW Engine-Driven Generator. Fuel consumption is the only performance parameter of the thermoelectric power source which falls short of the engine-driven generator set characteristics listed in Table 1.

TABLE 1. Performance Characteristics of 500-Watt Thermoelectric Power Source and 0.5 kW Engine-Driven Generator

	500-Watt Thermoelectric Power Source	0.5 kW Engine-Driven Generator
Operational Fuel	Gasoline, Diesel, JP-4, JP-5 Kerosene	Gasoline only
Acoustic Noise	Silent - inaudible at 100 m	Industrial noise level - audible at 500 m
Weight	30 kg (66 pounds)	38 kg (85 pounds)
MTBF	2,000 hours	250 hours
Maintenance	No moving parts, no lubrication, clean burner after 100 operating hours	Frequent periodic maintenance - 150 operating hours
Fuel Consumption	1.35 kg/hour (0.46 gal/hour)	0.73 kg/hour (0.25 gal/hour)
Operational Temperature Range	$-31^{\circ}C$ to $+51^{\circ}C$	$-31^{\circ}C$ to $+51^{\circ}C$

Discussion

A cross-sectional view of the present burner-converter assembly of the 500-Watt Thermoelectric Power Source is shown in Figure 3.

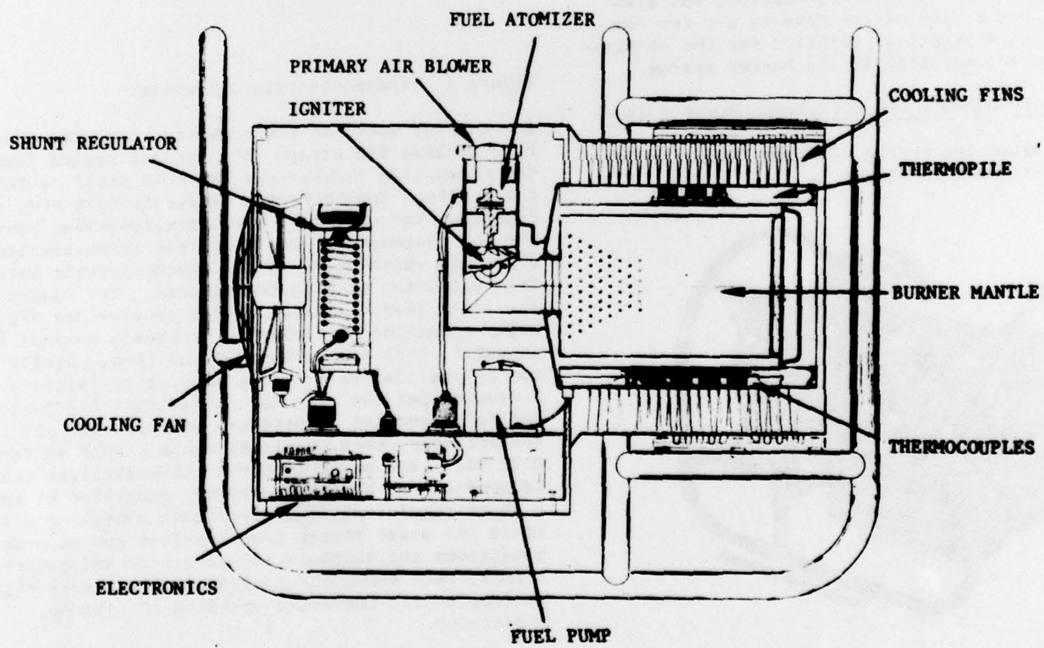

Figure 3. Cross-Sectional View of the 500-Watt Thermoelectric Power Source

The setting of the output power control establishes the basic amount of fuel required to operate the unit. This fuel is continuously injected into the atomizer by an electrically driven fuel pump. The pump motor is controlled by a logic circuitry which senses the electrical output of the thermopile and automatically corrects the required fuel flow rate to avoid over-heating the thermopile in case of excessively high environmental temperatures or deficiencies of the cooling system. The fuel atomizer is a transducer which conditions the liquid hydrocarbon to produce a continuous mist of fuel for combustion. The transducer assembly is located inside the burner tube and is axially mounted in the middle of the primary air stream. The fuel mist is mixed with the primary air which is provided by a brushless type blower.

The combustion process is initiated by a spark gap igniter. Combustion commences near the tip of the atomizer and continues to completion inside the mantle of the combustion chamber. The mantle allows the required residence time for the combusting gases and directs them on the heat transfer fins of the converter. Combustion products leave the unit through peripheral openings equally spaced at the end of the cylindrical mantle.

A temperature difference must exist between the exhaust gas and the hot junction of the lead telluride couples. With the requirement for an operational 565°C hot junction temperature of the thermopile,[2] the combusted gases leave the mantle at a temperature (T_{ex}) of approximately 700°C. The amount of heat, Q_{ex}, which they dump into the atmosphere, can be calculated from

$$Q_{ex} = (m_f + m_a)\, C_p\, (T_{ex} - T_a)$$

where

m_f = the mass flow rate of fuel

m_a = the mass flow rate of primary air for combustion

C_p = the specific heat at constant pressure of the exhaust gases

T_{ex} = the temperature of the exhaust gases

T_a = the ambient temperature

Q_{ex} amounts to approximately 40 percent of the heat content of the fuel. The balance (60 percent) of the heat released by the combustion passes through the thermoelectric converter. Seven (7) percent of this heat is converted into electric power by the thermopile (equivalent to 640 electrical watts). The remaining heat, amounting to approximately 56 percent of the total heat content of the fuel, is removed from the unit by the cooling air.

Because the operational temperature on the cold side of the thermopile is maintained at 162°C, the cooling air is heated to a temperature of 85°C, which is too low for practical methods of heat recovery. The combustion products, which leave the unit at 700°C, contain considerable heat at a relatively high temperature. A large percentage of this heat can be recovered through preheating the primary air for combustion. An air-to-air heat exchanger was devised for this purpose. The heat exchanger, which is assembled at the exit of the combustion chamber, was designed for minimum size without introducing excessive impedance in the line of primary air for combustion. Figure 4 is a top view of the heat exchanger which retrofits the top of the existing combustion chamber.

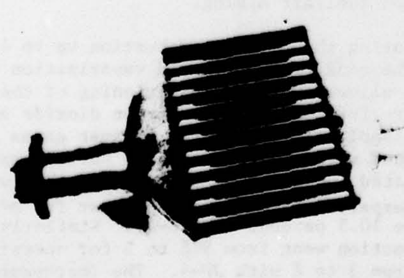

Figure 4. Experimental Heat Exchanger

It is comprised of an array of 102 stainless steel tubing sections arranged in a three-fold pass. It has demonstrated the capability of preheating ambient air up to a temperature of 500°C at flow rates between 300 and 500 liters/minute.

The output of the air-to-air heat exchanger is channeled to the burner through a duct on the outside of the unit. Two components, located inside the burner, have been relocated in the regenerative burner system configuration (Figure 5). The primary air blower is positioned at the ambient air inlet port of the heat exchanger. The atomizer transducer, which cannot operate in environmental temperatures above 80°C, is mounted outside the burner tube. Atomized fuel is transversally injected into the heated primary air stream.

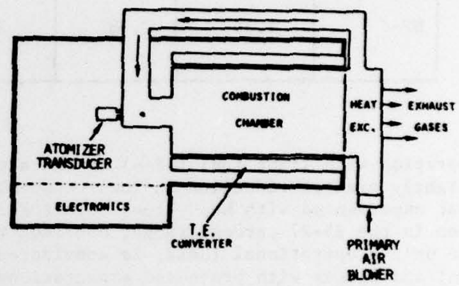

Figure 5. Schematic Diagram of the 500-Watt Thermoelectric Power Source Incorporating the Regenerative Burner System

Since preheated air enters the combustion chamber at an elevated temperature (400 to 500°C), a considerably lower fuel flow rate is needed to maintain the combustion chamber at the operational temperature required by the thermoelectric converter. The air-to-air heat exchanger and the recycling hardware have been configured in an easily assembled structure to permit comparative evaluation, under the same environmental conditions, with and without the preheating of the primary air. A heat exchanger with related hardware to recycle the preheated air, is shown, assembled on a 500-Watt Thermoelectric Power Source, in Figure 6.

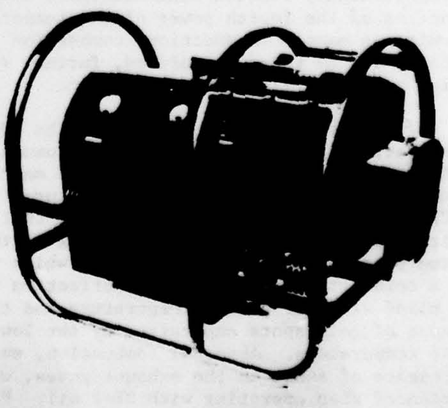

Figure 6. Heat Exchanger Assembled on the 500-Watt Thermoelectric Power Source

This unit has been tested with JP-4 (jet fuel), gasoline, and DF-2 (diesel fuel oil). The results, in terms of fuel consumption and corresponding overall efficiency, are presented in Table 2.

TABLE 2. Comparative Performances of the 500-Watt Thermoelectric Power Source

	Primary Air for Combustion at Room Temperature			Preheated Air for Combustion				
Fuel Type	Fuel Consumption Kg/h	Unit Overall Efficiency %	Primary Air Temperature °C	Fuel Consumption Kg/h	Unit Overall Efficiency %	Primary Air Temperature °C	Fuel Reduction %	Unit Efficiency Increase %
JP-4	1.4	3.0	23	1.02	4.1	415	27	36.7
Gasoline	1.35	3.1	23	1.01	4.15	410	25.2	34
DF-2	1.38	2.98	23	1.04	3.96	409	25	33

Operation with light fuel (JP-4) is characterized by a slightly greater reduction in fuel consumption than that experienced with heavy fuel oils (DF-2). Reduction in the 25-27 percent range, obtained with all of the unit's operational fuels, is considered significant and agrees with projected expectations based on calculated efficiency of the air-to-air heat exchanger. Heat losses, present in the configuration of this prototype heat exchanger, are estimated to be approximately 15 percent. Therefore, additional gain in fuel saving is anticipated with an improved regenerative burner system design. The lower fuel requirement for the operation of the thermoelectric power source effects a corresponding reduction in the flow rate of the primary air. Thus, despite the increased fluid dynamic impedance of the air line due to the addition of the heat exchanger structure, an 8-10 watt reduction in the power requirement for the primary air blower resulted.

The tests performed have also indicated two additional areas of improved performance relative to the location of the heat exchanger at the exit of the combustion chamber. Temperature of the exhaust gases is reduced from 700°C to 240°C. The infrared signature detection of the unit and combustion products is now significantly reduced since infrared emission is a function of the fourth power of the temperature of the emitting mass. In addition, combustion noise in the 63 to 500 Hz range is muffled, further reducing the low noise profile of the unit.

During outdoor winter testing of the 500-Watt Thermoelectric Power Source, carbon accumulation occurred inside the burner tube and the mantle when the unit was operated in a low temperature (below -25°C) environment. Analysis indicated that this condition was caused by local quenching of the combustion process in its initial phase, which resulted from a combination of reduced vaporization rate of fuel mixed with air at low temperature and the presence of cold spots emphasized by the low operational temperature. Abnormal combustion, evidenced by presence of smoke in the exhaust gases, was also experienced when operating with DF-2 oil. Partial clogging of the small holes in the mantle, which occurred after prolonged operation, was evidence of incomplete combustion of heavy fuels. This condition will compromise the low maintenance goal for this power source by requiring periodic cleaning.

The standard Bacharach scale is used to determine the smoke level. An exceptionally clean, smokeless fire is zero (0) on this scale. A Bacharach number of 10 is the highest smoke level measured and corresponds to a dirty fire, which will cause rapid sooting and fouling. High reliability burners are normally adjusted to No. 2 or 3 smoke. Scale readings over No. 6 smoke are usually considered unacceptable conditions which can cause inoperability in a short period of time. The level of smoke relates to the amount of pollutants dumped into the atmosphere and to the continuing reliability of the burner, but it does not directly relate to the efficiency of the combustion. By providing enough excess combustion air, a burner can be adjusted for minimum smoke. However, this is done at the expense of the efficiency and heat transfer capability of the burner and imposes a higher power requirement for the primary air blower. It is possible to assess combustion efficiency by measuring the percent of CO_2 present in the combustion products, which is indicative of the degree of completion of the combustion process. For a well designed and properly operating burner, the following two conditions must be present simultaneously; a) a high percent CO_2 reading, which is the measure of complete combustion and proper stoichiometric ratio, and b) a low smoke number, which is an indication of good fuel/air mixing.

Preheating the air for combustion up to 450-500°C provides the condition for rapid vaporization of the fuel which allows improved conditioning of the air/fuel mixture for combustion. Carbon dioxide analysis and smoke sample testing of the exhaust gases of the unit equipped with the regenerative burner system have indicated increases in CO_2 content that were less than expected (from 8 to 9 percent for DF-2, and from 9.5 to 10.5 percent for JP-4). Similarly, smoke number reduction went from 5.5 to 5 for operation with DF-2 and from 3 to 2 with JP-4. The improvements obtained are considered marginal and, in the case of

operation with heavy fuel oils, combustion is still considered unsatisfactory. The relocation of the atomizer transducer from inside to outside the burner tube, as illustrated in Figure 5, does not modify the relative distance between atomizer tip and ignition point. Therefore, the potential gain in fuel vaporization, which should be provided by the preheating of the air for combustion, is not achieved because of the low residence time allowed for the mixing of the fuel with air.

Attempts of a farther relocation of the atomizer transducer from the ignition point are being investigated. Figure 7 shows a cross-sectional view of the regenerative burner system with the atomizer positioned between the primary air blower and air-to-air heat exchanger.

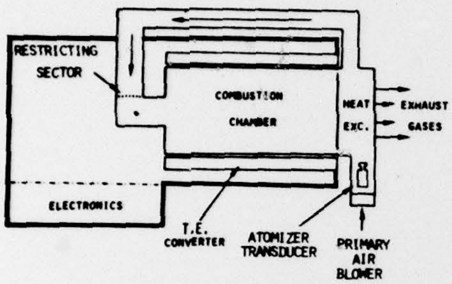

Figure 7. Schematic Diagram of the 500-Watt Thermoelectric Power Source Showing the Relocation of the Atomizer

In this configuration the air/fuel mixing occurs before the heat exchanger section, so that the entire mixture is preheated. The result is a more complete vaporization of the fuel and a longer residence time before ignition occurs and combustion starts. Combustion patterns of this arrangement of the burner components were analyzed on tests run with an open mantle (not surrounded by a thermoelectric converter). They are characterized by an extremely uniform temperature distribution, indicative of the high degree of air/fuel mixing achieved. The final implementation of this configuration is hampered by two basic problems. First, operation of the unit with normal air flow rates, corresponding to stoichiometric ratios in the 1.2-1.4 range, triggers periodic flame-back. Second, during the start-up procedure, the air-to-air heat exchanger traps a significant portion of the fuel, and ignition of the too lean mixture occurs sporadically.

Combustion is characterized by a flame front velocity which depends upon the thermodynamic conditions of the environment where the process takes place and upon the nature of the combusting gas. In the burner system of the 500-Watt Thermoelectric Power Source, the flame front velocity exceeds (for all fuels tested) the mass velocity of the incoming air/fuel mixture. Consequently, the combustion front moves, along the duct, to the exit of the heat exchanger creating an unsafe condition. To correct the flame-back condition, a metallic sector was installed inside the burner tube and positioned two centimeters in front of the igniter. By properly sizing the restricting sector holes, the velocity of the air/fuel mixture can be locally increased to exceed the velocity of the flame front which is thereby stabilized. A properly designed restricting sector provides satisfactory results in confining the combustion flame in the burner tube, however, its presence in the air stream line creates a high additional impedance which more than doubles the power requirement for the primary air blower.

Preliminary data, obtained during the few cases when combustion was successfully initiated and when the restricting sector allowed proper operation, indicate satisfactory improvements in the combustion process. Visual inspection, at the end of these tests, evidenced an extremely clean mantle and burner components. This suggests that, when the existing deficiencies are fully corrected, this optimal regenerative burner configuration will eliminate the carbon accumulation in the critical parts of the system.

Conclusions

The prototype regenerative burner system designed for the 500-Watt Thermoelectric Power Source demonstrates the practical possibility of reducing the fuel consumption by recovering part of the heat dissipated into the atmosphere by the combustion products. The results obtained are significant with respect to fuel saving (25-27 percent) and a corresponding increase of overall efficiency (33-36 percent).

Tests indicate that other improvements in the operation of the 500-Watt Thermoelectric Power Source have been achieved. Utilizing the heat exchanger section at the exit of the combustion chamber, the exhaust gas temperature is lowered, which significantly reduces the infrared signature detection of the unit, and combustion noise is muffled, which lowers the acoustic noise profile of this power source.

A practical means of solving the carbon accumulation problem can be derived from the preheating of the primary air for combustion. Application of the regenerative burner system will be further investigated through the development of an improved air-to-air heat exchanger design, utilizing a simpler structure and higher heat transfer capability material.

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